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Sensor and Actuator Technology Development

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Outline

- Sensor and Actuator Placement for Robustness
- Self-Sensing Actuators
- Nonlinear Actuation Models

Sensor/Actuator Selection

- Sensor and actuator selection/placement sets an *a priori* limit on closed loop performance.
- Correct placement can improve nominal performance for any specific control design technique.
- Placement problem has been investigated previously
 - open loop vs. closed loop algorithms
 - optimal vs. heuristic algorithms
- Degrees of freedom for sensor and actuator suite design:

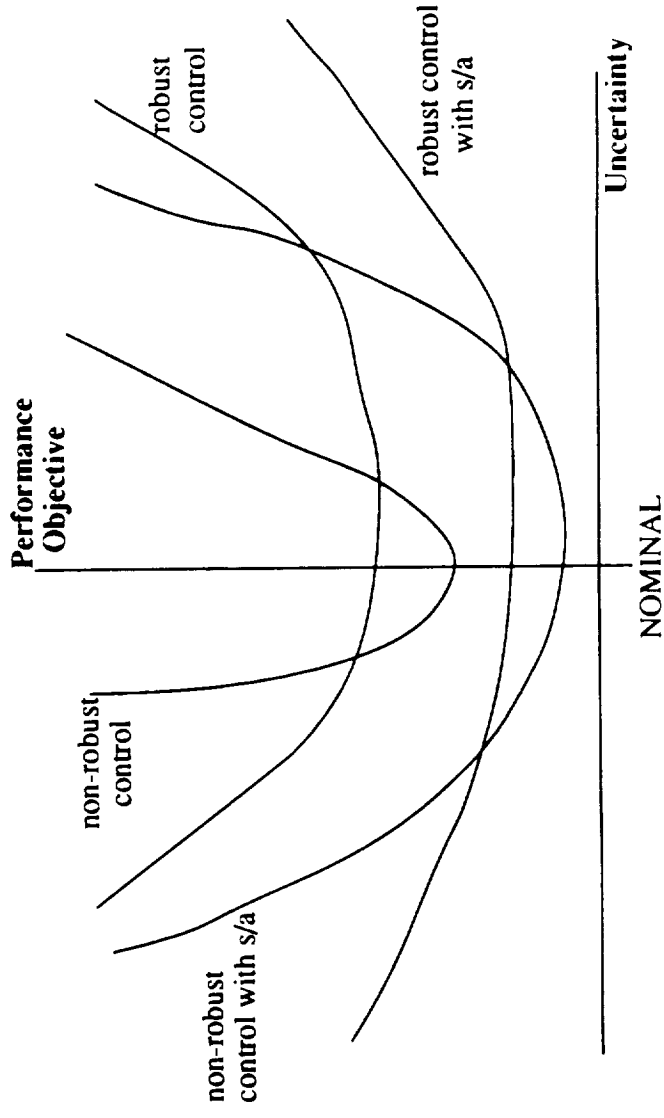
Number	Type	Location	subject to design constraints
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- Placement is typically done using initial inaccurate model.

Sensor/Actuator Selection for Robustness

- Concept: Select sensors and actuators to minimize impact of model inaccuracies on achievable performance and stability.
- Motivation:
 - Placement and resulting closed-loop performance \stability are a strong function of model.
 - Only have uncertain model on which to base placement decisions.
 - Implies large uncertainties in *achievable* closed-loop performance or robustness.
- Method: Incorporate model uncertainty information into open or closed loop placement algorithms.

Achievable Performance Robustness

- Control design must use actuator and sensors it is given.
 - Example: Loss of controllability when actuator is unwittingly placed at a node.
- Can enable control task by introducing performance robustness through s/a set.



Representing the Uncertain System

- All system matrices affected by model uncertainty
- Focus on finite element errors, not ID errors
- Determine eigenvector uncertainty to expected errors:
 - Stiffness of components
 - Boundary conditions
 - Mass distribution
- Two approaches:
 - *Range* of possible plants/systems over all uncertain parameters
 - *Sensitivity* of nominal plant/system to uncertain parameters

Figures of Merit

- Open loop analysis of sensor/actuator options used to reduce number of choices to manageable number
- Use controllability and observability gramians

$$W_c(t_0, t_1) = \int_{t_0}^{t_1} \phi(t_1, \tau) B(\tau) \phi^T(t_1, \tau) d\tau$$

- Calculate with Lyapunov equation for each value of uncertainty

$$0 = A_i W_{c_i} + W_{c_i} A_i^T + B_i \sum_{ww} B_i^T ;$$

- Closed loop cost

$$J_{cl} = \text{tr} \{ \langle Q C_i^T C_i \rangle \}$$

where

$$0 = A_i Q_i + Q_i A_i^T + B_i B_i^T$$

Design Algorithms

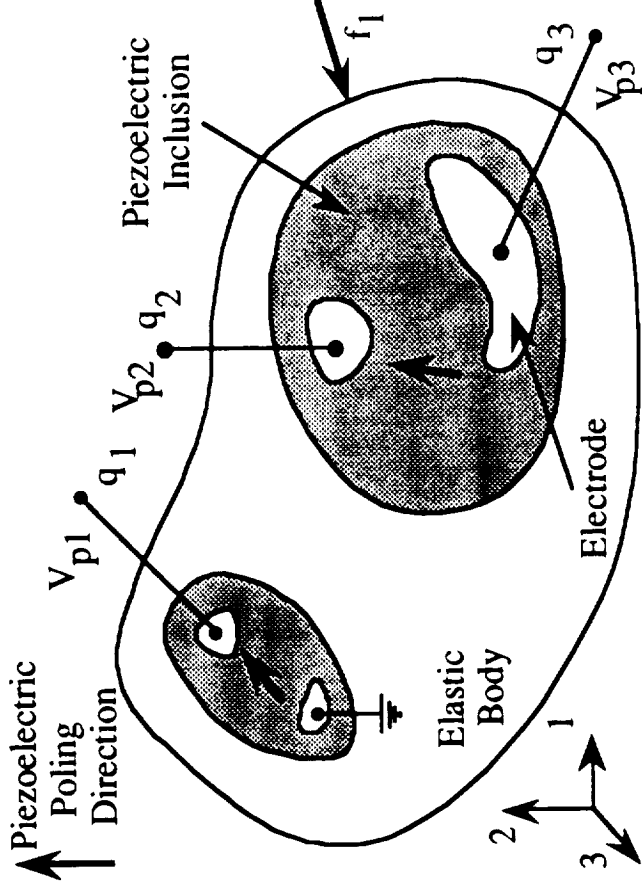
- Open loop
 - Compute expected value of gramians over entire uncertainty set
 - Reduce number of s/a options by straight ranking
- Closed loop
 - Use existing techniques for optimization
 - Cost is expected value over uncertainty set
- Trade off degree of open loop reduction vs. size of set for closed loop optimization

Current Efforts

- Analytical sample problem: cantilevered beam
 - 6 sensors, 6 actuators
 - LQG control (SISO and TITO)
- Interferometer testbed
 - Analysis based on finite element model
 - Uncertainty description provided from system ID data
 - Main focus is active strut placement problem
 - Experimental demonstration of improved closed loop performance based on sensor/actuator location and type

Piezoelectric Actuation and Sensing

- Structure with piezoelectric actuators/sensors.



- Governing Equations of Motion:

$$(\mathbf{M}_s + \mathbf{M}_p) \ddot{\mathbf{r}} + (\mathbf{K}_s + \mathbf{K}_p) \mathbf{r} - \Theta \mathbf{v} = \mathbf{B}_f \mathbf{f} \text{ Actuator Eq.}$$

$$\Theta^T \mathbf{r} + \mathbf{C}_p \mathbf{v} = \mathbf{B}_q \mathbf{q} \text{ Sensor Eq.}$$

Simultaneous Sensing and Actuation

- Concept: Use the same piece of piezoelectric simultaneously as both a structural sensor and an actuator.
- Motivation:
 - Eliminates need for separate sensor. Reduced signal conditioning.
 - Perfectly collocated dual sensor useful for structural control.
- Modelling: If the applied current and piezoelectric electrode voltage is known, one can reconstruct the mechanical strain or strain rate.

$$\Theta^T \mathbf{r} = \mathbf{q} - \mathbf{C}_p \mathbf{v} \quad \Theta^T \dot{\mathbf{r}} = \mathbf{i} - \mathbf{C}_p \dot{\mathbf{v}}$$

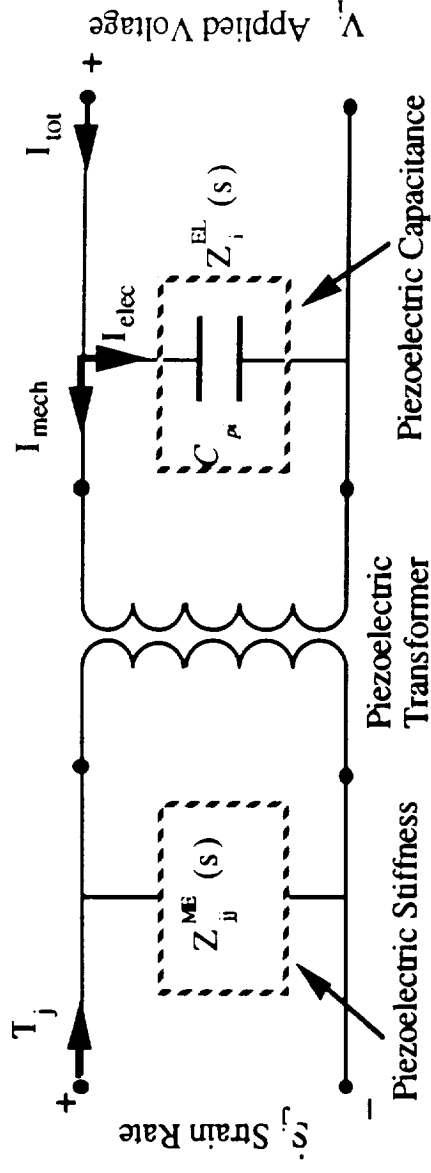
- The $\Theta^T \mathbf{r}$ term is proportional to averaged strain state as for the charge based sensor.

$$\Theta^T \mathbf{r} = \int_{V_p} [\mathbf{e}_{31} S_1 + \mathbf{e}_{31} S_2 + \mathbf{e}_{33} S_3] dv$$

- More insight can be gained on the physical significance of the terms by using a piezoelectric circuit analogy.

Physical Interpretation

- The piezoelectric transformer analogy is useful for determining the physical significance of the terms. The piezoelectric element is represented as a transformer converting mechanical energy to electrical and vice versa.

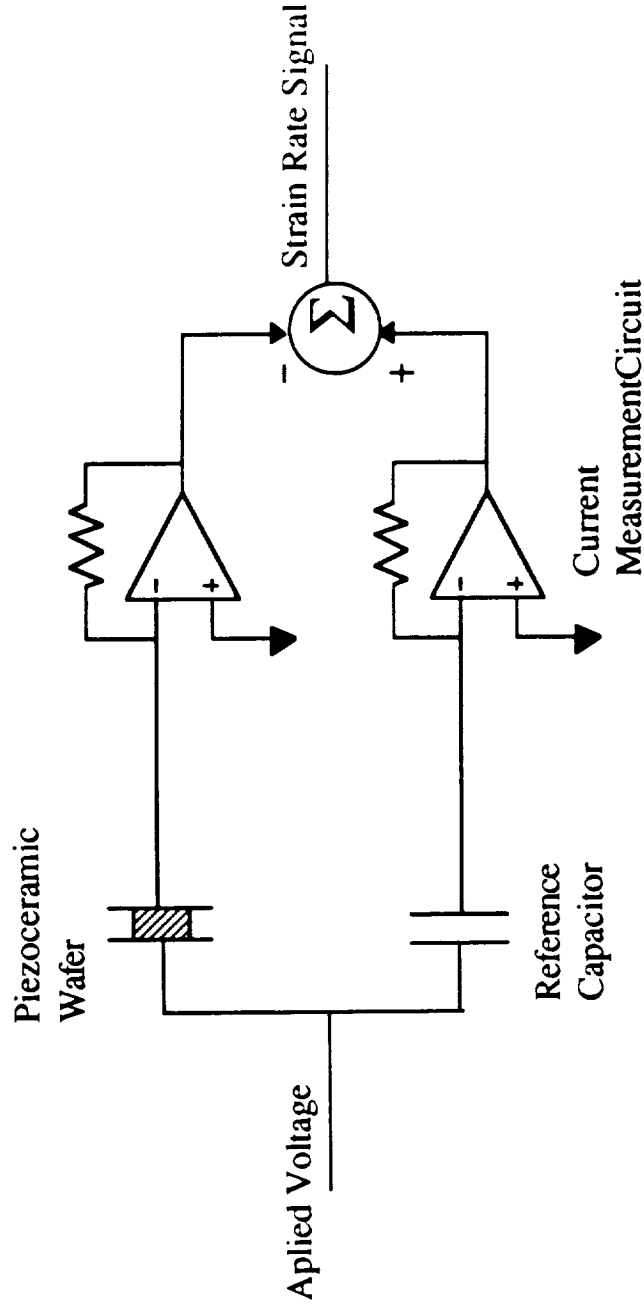


- The sensor equation can be interpreted physically as measuring the difference in between applied current and the capacitance current.

$$\Theta^T \dot{\mathbf{r}} = \underbrace{\dot{\mathbf{i}}}_{\dot{\mathbf{i}}_{mech}} - \underbrace{C_p \dot{\mathbf{v}}}_{\dot{\mathbf{i}}_{elec}}$$

Simple Circuit Implementation

- Strain Rate Circuit

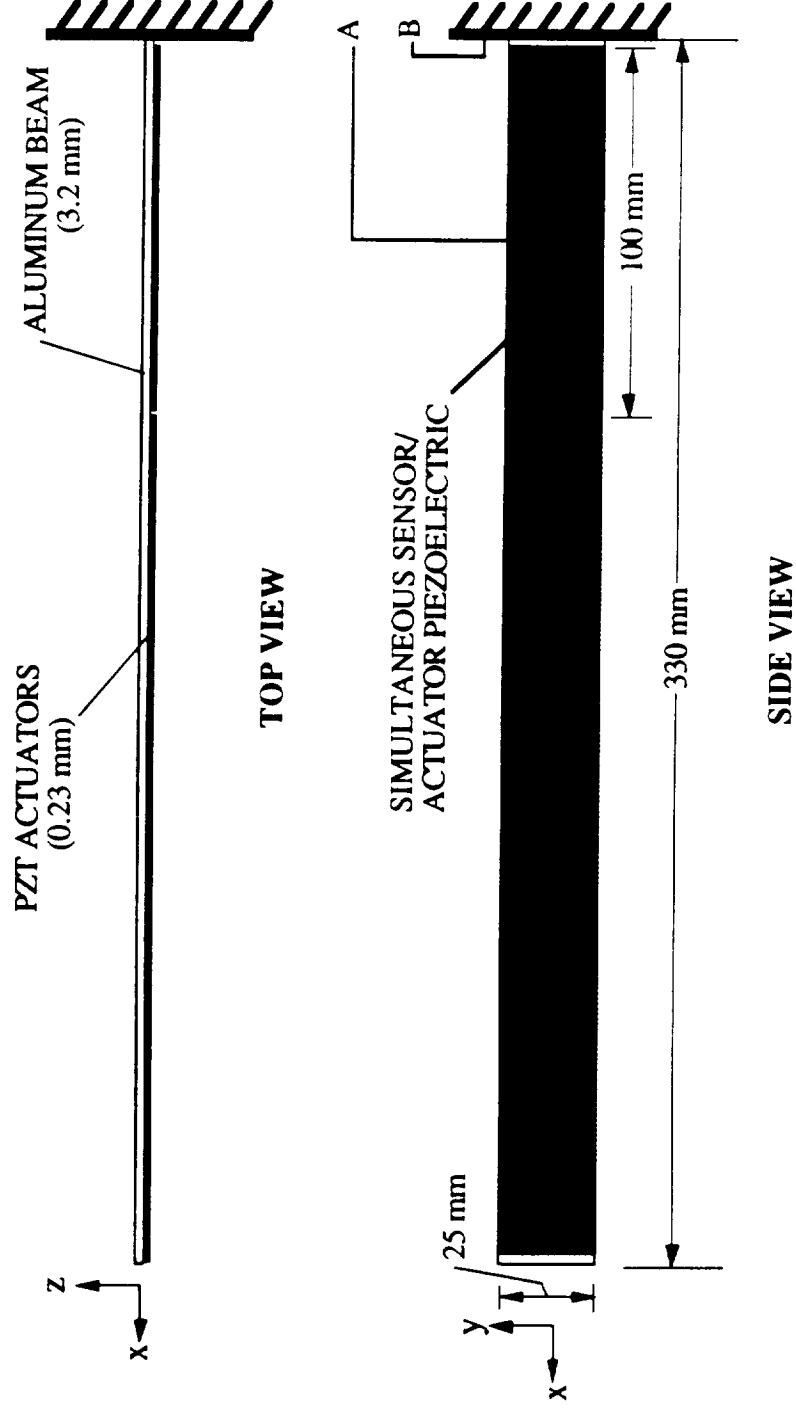


B) Strain-Rate Sensing Configuration

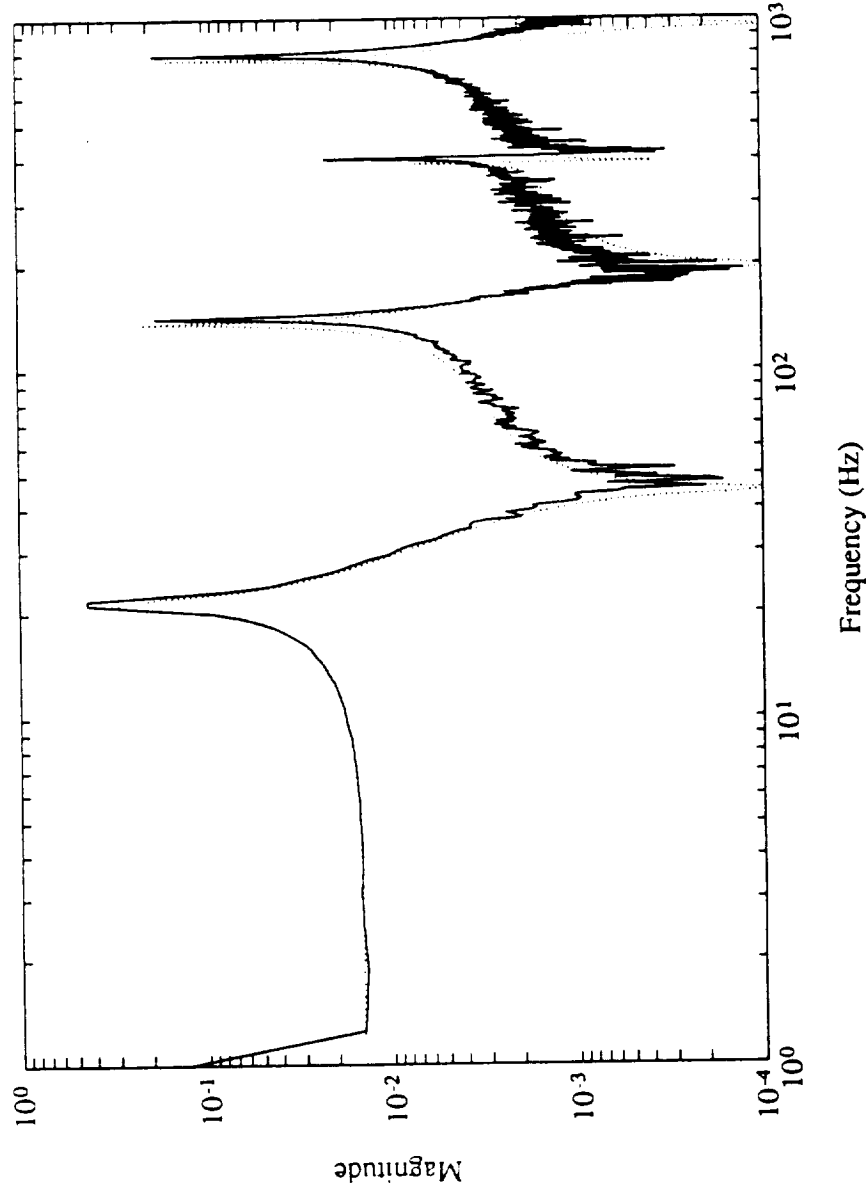
- Also possible to implement simple strain sensing circuit by measuring applied charge rather than current.

System for Experimental Demonstration

- Cantilevered beam with PZT wafers on the surface.



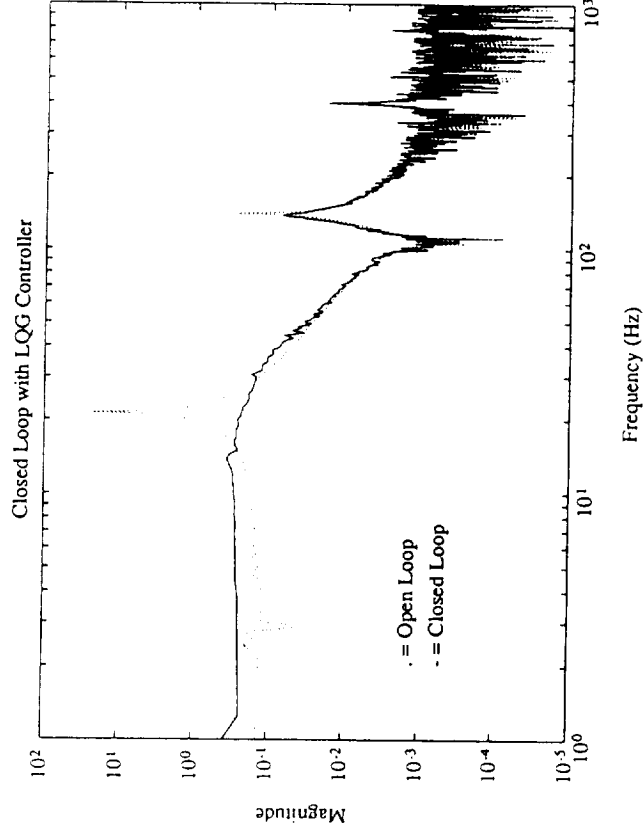
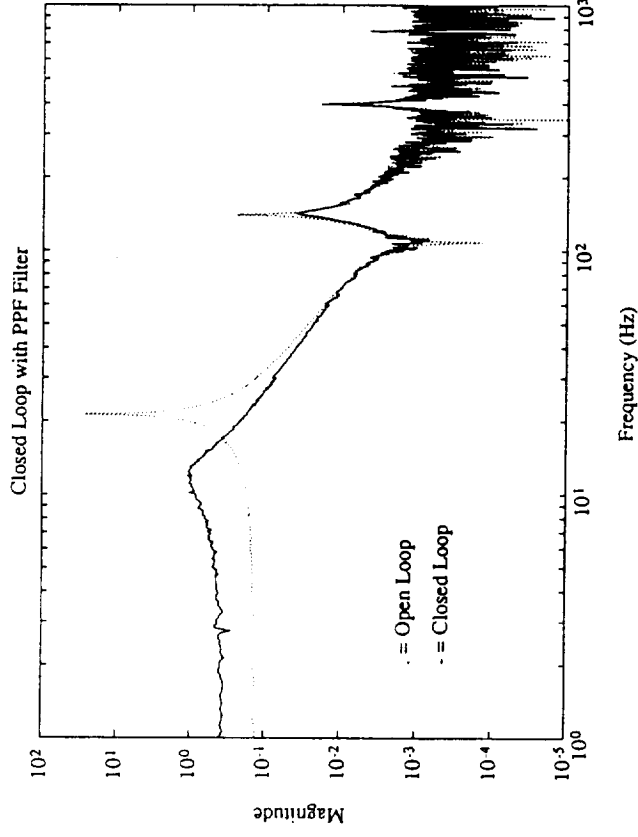
Open Loop Results



- Model compares well with measurement
- Zero location matching hindered by PZT hysteresis

Closed Loop Results

- Tip displacement/force input with “sensuator” loop closed



- Positive position feedback (PPF)
- LQG

Applications

- Retrofit of sensing capability on existing actuator systems
 - Information on local deformation
 - Information for collocated control (addition of damping)
- Linearization of actuator response
- Health monitoring and system identification
- Active structural control (high gain collocated loops)

Nonlinear Actuation Models

- Concept: Develop models of actuated structures capable of handling actuation material nonlinearities
- Motivation:
 - Piezoelectric material properties are nonlinear at high strains.
 - Higher actuation performance available from inherently nonlinear materials.Electrostrictive materials
New high-strain, shape-memory ceramics.
- Approach:
 - Microscopic material models for capturing relevant physics.
 - Macroscopic phenomenological models for nonlinear structural response using energy methods.

Conclusions

- Ongoing work in three areas:
 - Robust Actuator and Sensor Placement
 - Self-Sensing Actuation
 - Nonlinear Actuation Modeling
- Robust actuator and sensor placement addresses a clear need but faces the difficulty of good error model development.
- Self-sensing actuation has been demonstrated and modeled, works well in active control systems for simple structures, and is being applied to built up structures.
- New research on nonlinear actuation models holds promise for high fidelity modeling of high strain actuation materials.